Fermilab

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Analysis on AccSys RFQ resonator model

G.Romanov, A.Lunin, T.Page

The assembly of the RFQ resonator designed and manufactured by AccSys for Fermilab has been completed and the initial tuning was performed on December 14, 2007. However, during the initial tuning of the resonator AccSys personnel were unable to correct (flatten) the resonator's quadrupole field. A number of attempts were made to bring the quadrupole field into a standard curve for tuning. The quadrupole field plot shows an extreme tilt, approx. 80% (see Fig.1). This is beyond the range of normal correction (i.e. end tuners and slugs) and indicates a serious, fundamental problem with the RFQ. (To place in perspective, the normal scale of the Y-axis on the quadrupole plot is 1.10 to 0.90). The cavity frequency was only 50 kHz under the final target frequency during initial RF measurements.

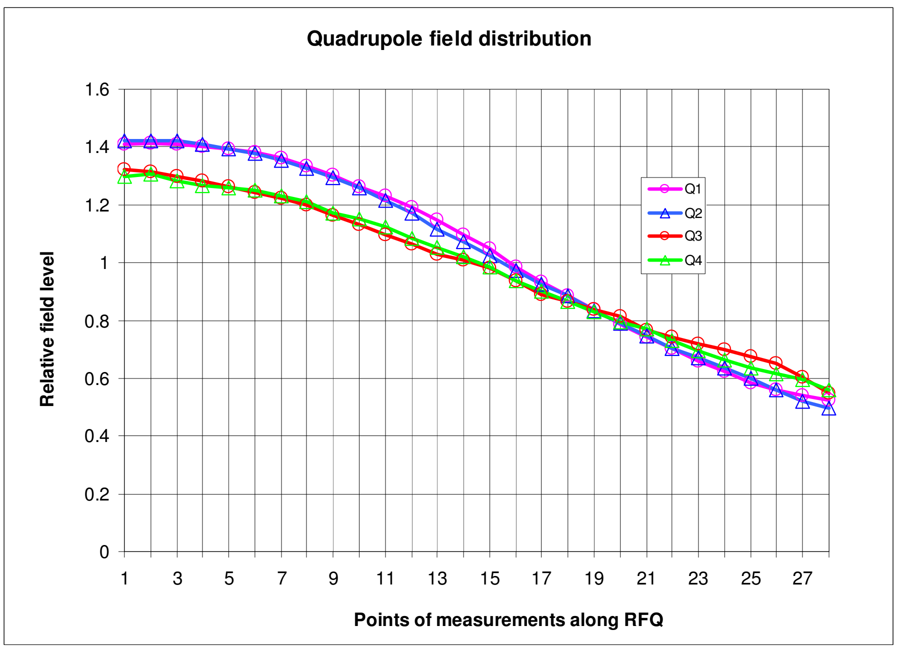

Fig.1 Initial quadrupole field distribution in four RFQ quadrants. Frequency 324.9 MHz.

Numerical simulations of the RF properties of the RFQ have been performed at FNAL with the use of MWS and HFSS to understand the problem and find a solution. The basis of the 3D RF model prepared for simulation were a solid model of RFQ univane developed by AccSys, some technical drawings of RFQ parts and mechanical measurements of actual critical dimensions. In the RF 3D model the end-wall tuners were set to a default value of 1.00" of penetration as it was during the initial RF measurements. The tuning slugs had no penetration into the cavity at that time. They were flush with the inner wall of the RFQ cavity, so the slugs were not included in RF model.

Cross-section

A cross-section of the RFQ resonator defines its main critical dimensions and RF parameters (quality factor, intervane voltage, power losses etc) based on beam physics specifications.

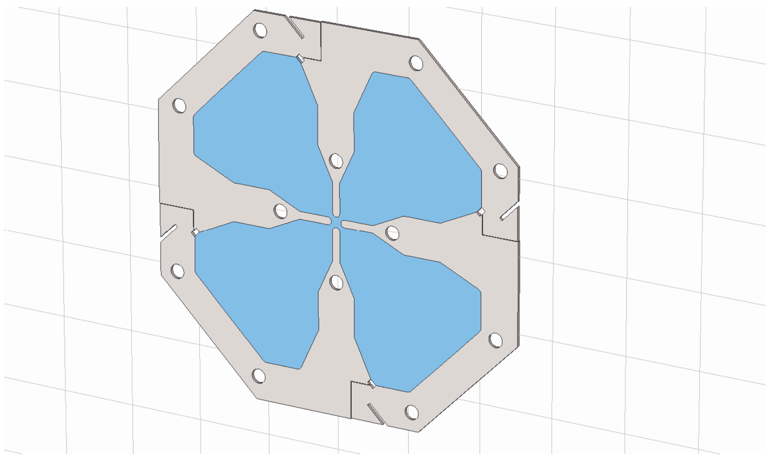

Fig.2 An RF model of RFQ resonator cross-section.

For our purposes, knowledge of the operating frequency of the quadrupole mode is important. Frequency of the dipole mode is also interesting to know. In Fig. 3 the magnetic field distributions of the fundamental quadrupole and dipole modes along with their frequencies are shown.

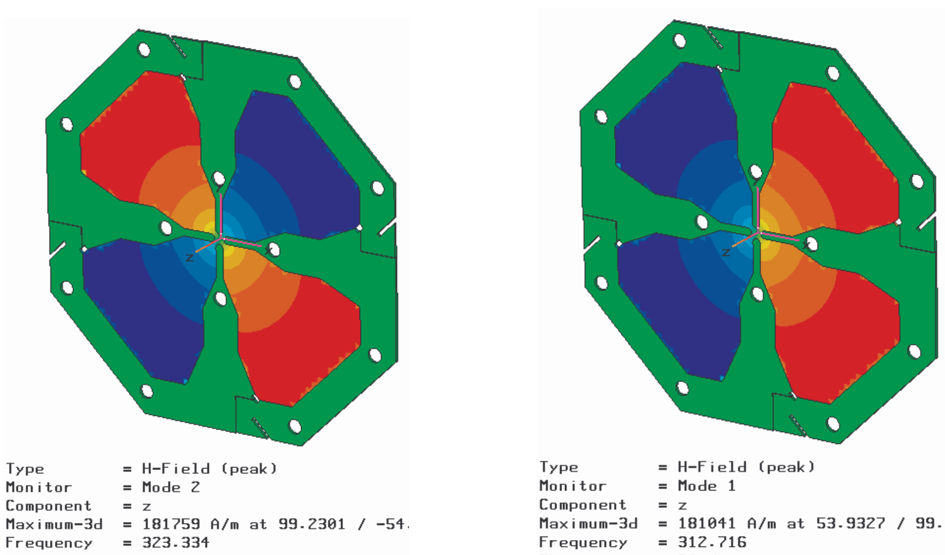

Fig.3 Distributions of peak magnetic field for quadrupole and dipole modes. Colors indicate direction of magnetic flow. Frequencies are 323.3 MHz and 312.7 MHz.

The operating frequency of 323.3 MHz is a good design value since the tuning slugs can only increase the frequency by penetrating into the RF volume.

Sensitivity of operating frequency to univane adjustment.

The patented AccSys univane construction insures that the RFQ vanes can be mechanically aligned to place the vane tips within ± 0.25 µm of the desired gaps. Nominally there are gaps of 0.254 mm between precision mating surfaces and shims are placed in the gaps between those surfaces (see Fig.4). Shims of different thickness can be used to adjust the gaps.

Simulations with different uniform gaps have been performed in order to estimate the dependence of the final frequency on the shim thickness.

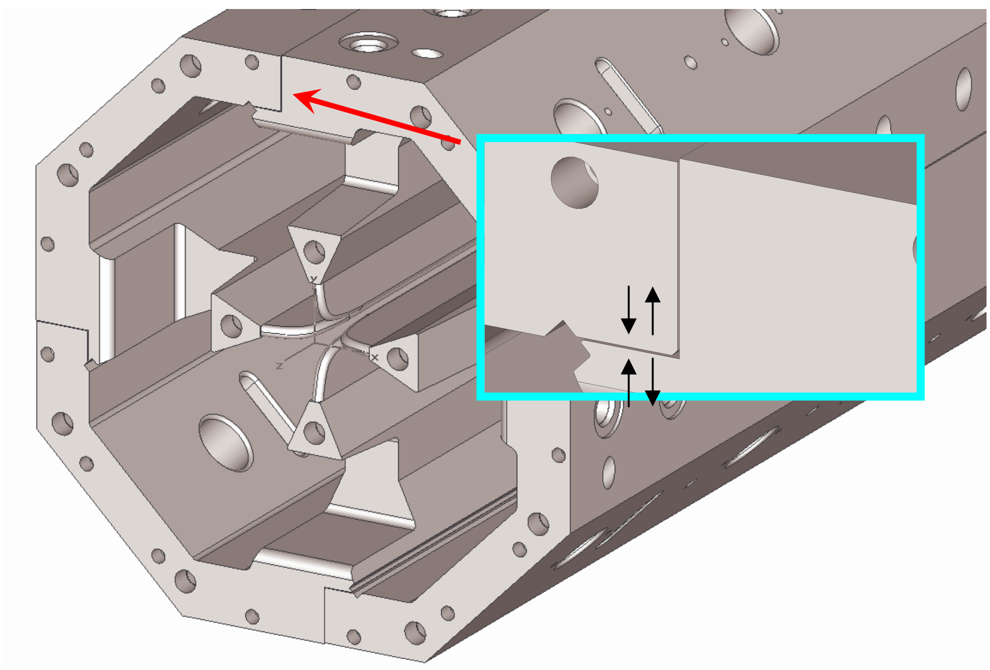

Fig.4 Variable gaps between univanes.

The sensitivity of the RFQ operating frequency to the mechanical alignment of the vane tips is very high. In our particular design the sensitivity is 0.027 MHz/µm. Since the vane assembly accuracy requirement is ± 30 µm, a local cross-section frequency variation of ± 0.81 MHz might be expected along the RFQ. This variation is supposed to be compensated by slug tuners.

Sensitivity of operating frequency to slug tuners.

The RFQ resonator has 16 slug tuners (cylinders of 25.4 mm diameter) in each quadrant to adjust the operating frequency and flatten the field distribution along the resonator. The distance between tuners is 140.8176 mm in the regular part of the RFQ resonator. A piece of structure of this length with one tuner in each quadrant has been simulated to obtain the tuning sensitivity of the tuners (see Fig.5). The simulation allowed equal penetration of all slug tuners to determine the corresponding frequency change of the entire resonator.

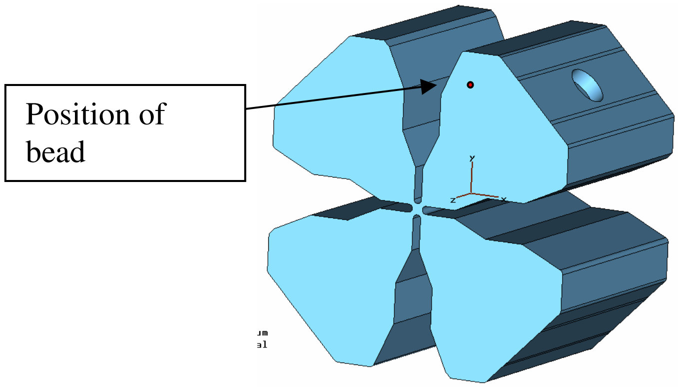

Fig.5. Portion of RFQ to simulate slug tuner sensitivity.

The operating frequency sensitivity to the slug penetration is 0.165 MHz/mm. The stroke of the slug tuners should be at least 10 mm to compensate for the frequency variation due to the vane assembly accuracy. More range may be necessary to compensate other possible errors.

Note.

For the bead pull measurements, the bead position is supposed to be somewhere in the quadrant corner, close to the wall, where the magnetic field is high and away from the slug tuners. The bumps created by the slug tuners will be visible at the indicated bead pull axis, as shown in magnetic field plot in Fig.6:

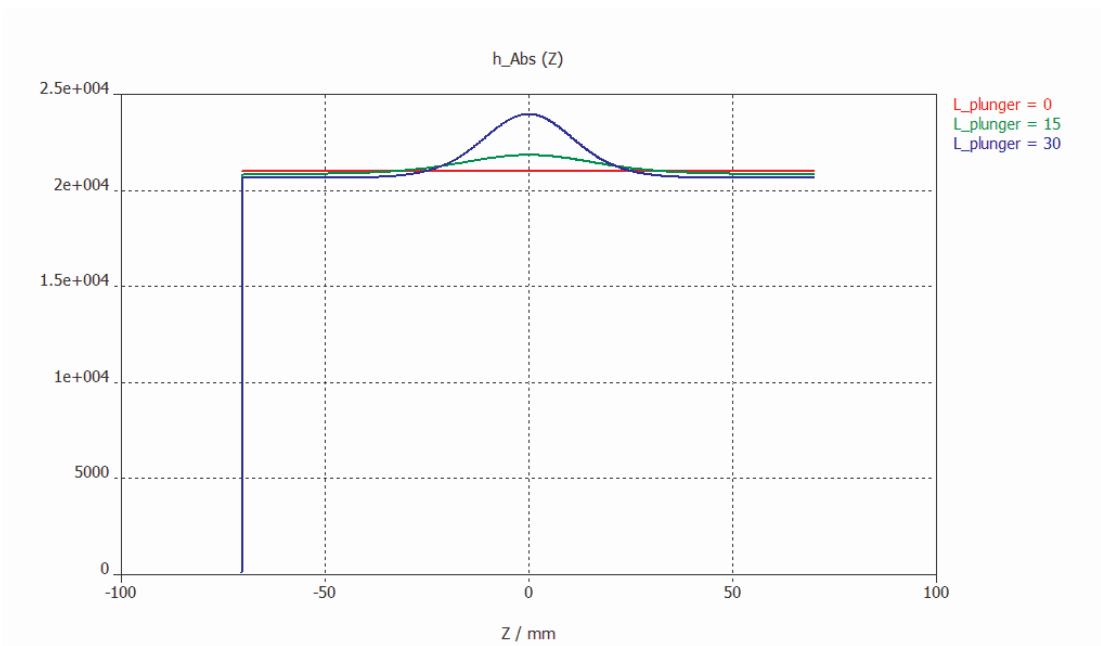

Fig.6. Absolute value of magnetic field along the proposed path of the bead for different penetration of the slug tuner. Units: mm.

Since the slug penetrations will most likely be different, the integrated field distribution plot may be somewhat confusing because of the bumps of different height.

Simulation of initial measurements. Full length model.

The simulations of the initial measurements have been performed on the model using the measured cut-backs of 56.2 mm for the input end and 59.8 mm for the output end. The measured and simulated field distributions are shown in Fig.7.

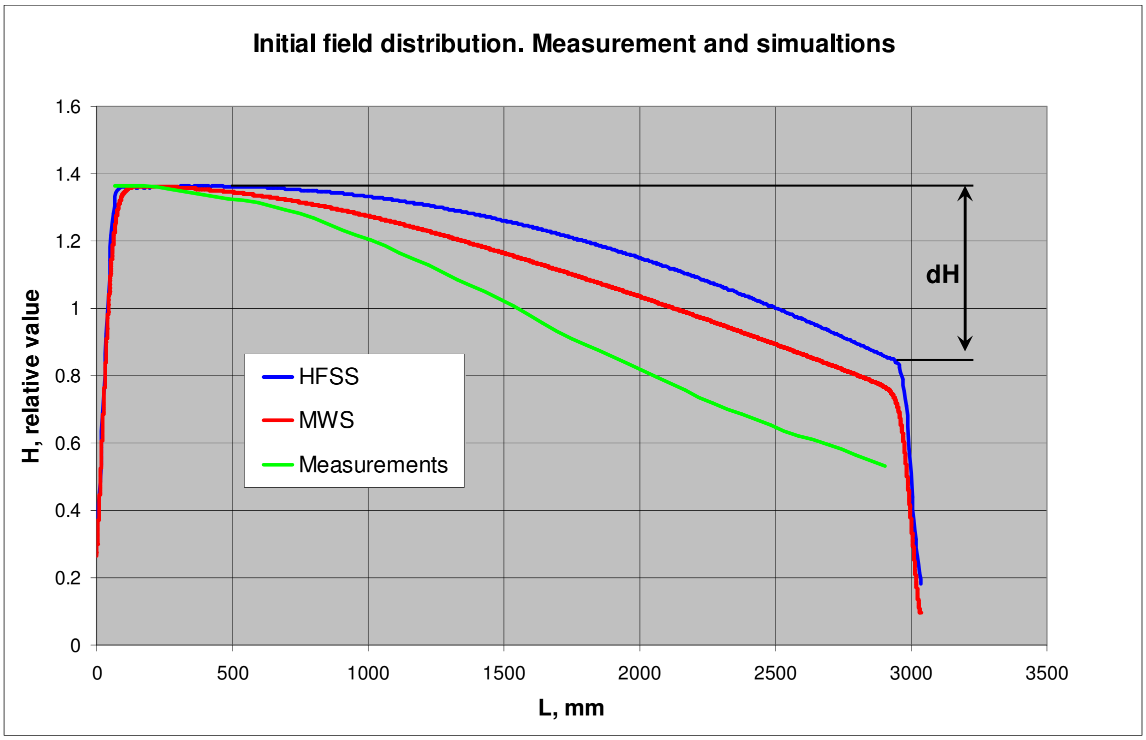

Fig.7. Plot of measured and simulated field distributions.

Both the MWS and HFSS simulations have a significant tilt of 44% and 38% accordingly (defined as $dH/H_{max}*100\%$). The simulated frequencies are 325.7 MHz (MWS) and 324.5 MHz (HFSS) while the measured frequency was 324.9 MHz.

Neither simulation reproduces exactly the measured field distribution. After some consideration, it was believed that there is additional frequency deviation along the RFQ regular body. It looks like 2/3 of the RFQ has a slightly higher frequency. This assumption has been checked with the model shown in Fig.8:

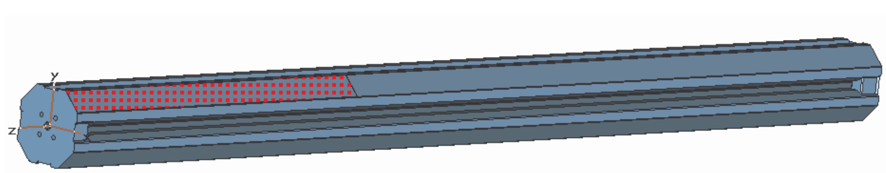

Fig.8. Selected part of RFQ body has nominal frequency, the other part has frequency higher by 1.3 MHz. The details for the rest of model are the same as the initial simulation.

Fig.9 shows the additional distortion of the field distribution due to this step variation of local frequency.

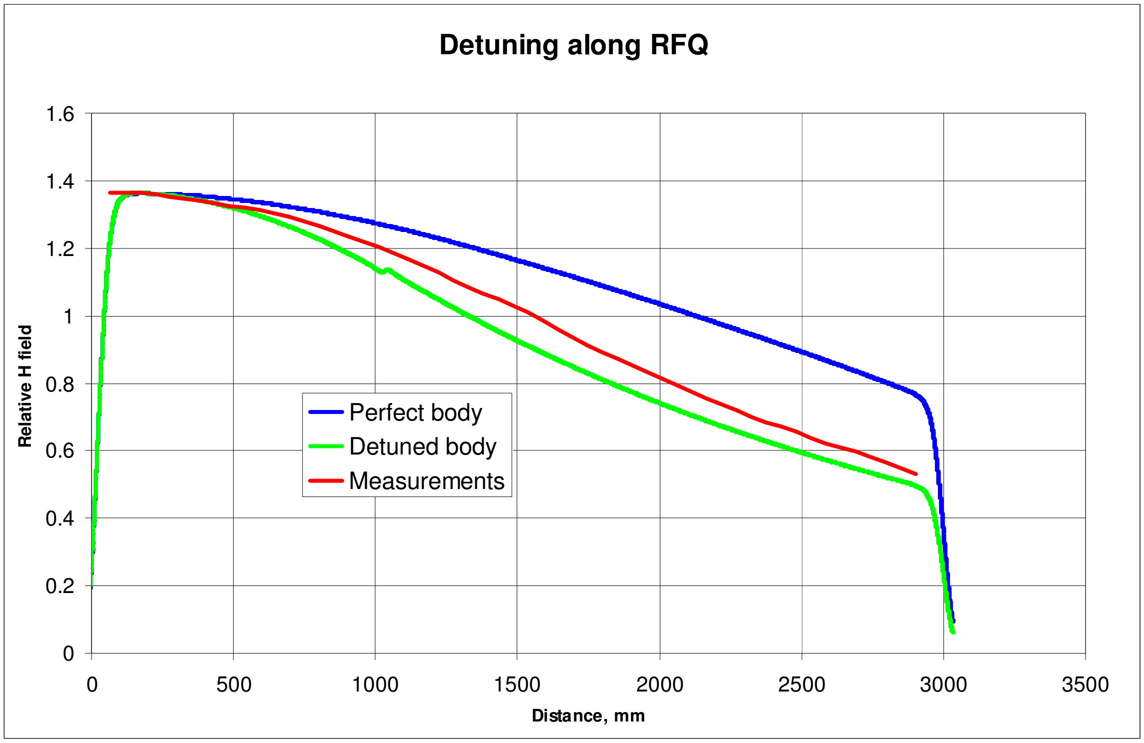

Fig.9. Additional distortion due to the frequency detuning along RFQ.

This detuning of 1.3 MHz may be the result of outer wall deviation by ~1 mm, or more likely, a deviation of the gap distance by ~48 μm (RMS tolerance is ± 30 μm). Whatever the reason, this 1.3 MHz can be removed by more accurate assembly and slug tuners. The main problem of the field distortion therefore is the detuned output matcher.

RF resonator tuning.

The tuning of the output matcher has been done with the use of ½ of full model. In this model the cut-back ramp of 5° has been removed and the back wall was moved inward (i.e. removing of material, see Fig. 10).

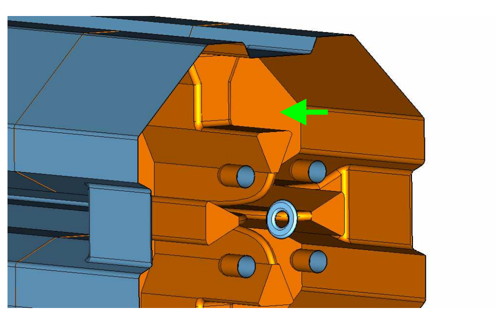

Fig.10. Model of revised cut-back details.

The field distribution tilt changes with increasing cut-back as shown in Fig.11.

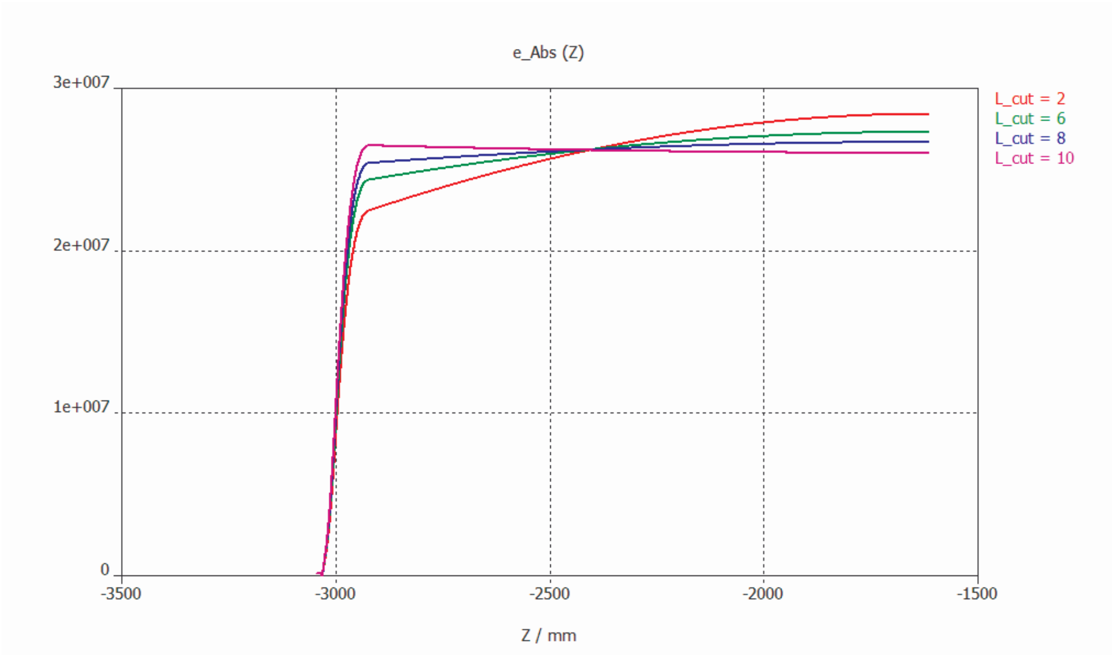

Fig.11. Field distribution with varying cut-back depths.

The optimal cut-back of 65.6 mm can be determined from the plot of tilt (see the definition above) vs. depth of cut-back as shown in Fig.12.

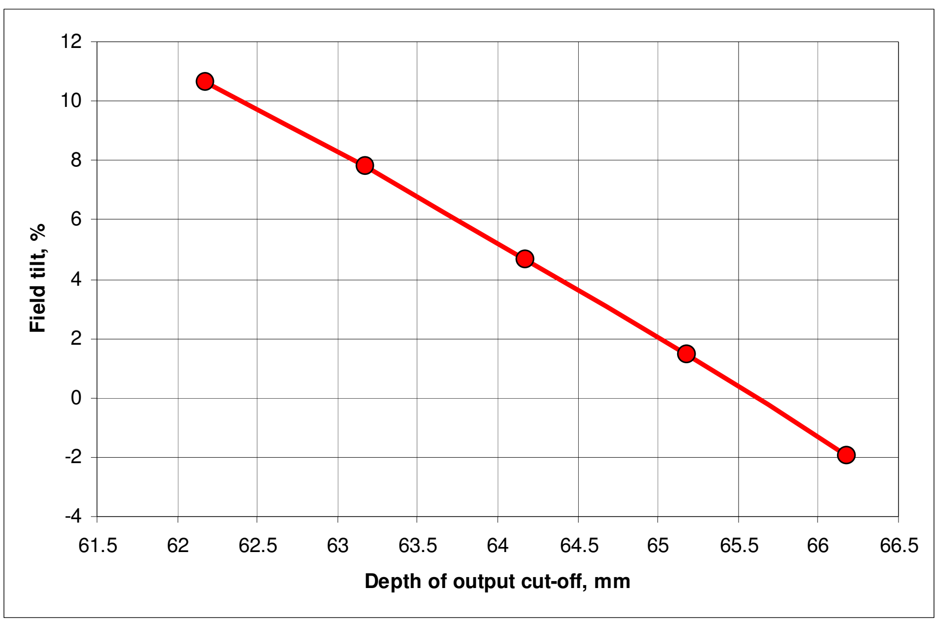

Fig.12. Tilt vs. cut-back depth.

Finally, the HFSS simulation on the full length model with the modified output cut-back has been performed to verify the result and is shown in Fig.13.

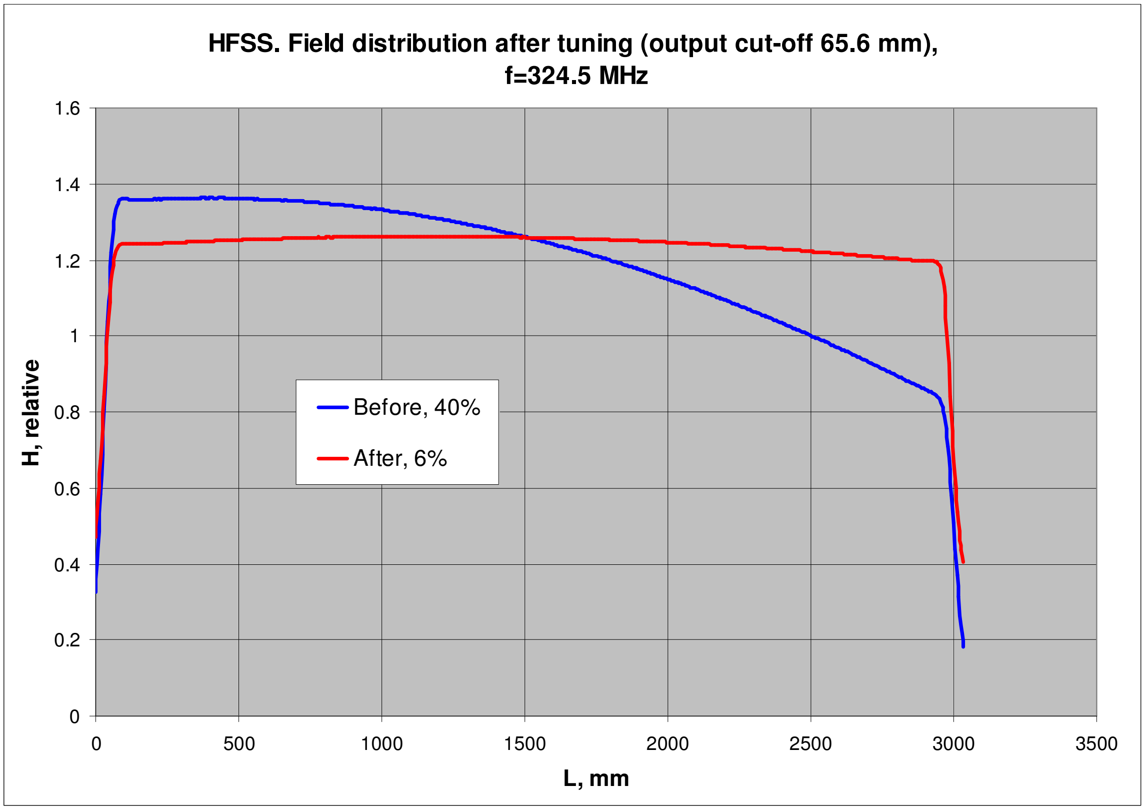

Fig.13. HFSS simulation with modified cut-back depth of 65.6 mm

Field distribution after this tuning is still not absolutely flat. The central part of the RFQ should be tuned to the operating frequency of 325 MHz and the central bump should disappear. Final touch may be done with end-wall tuners.

Proposed solution.

Based on the above simulations, the proposed solution to fix the RFQ is as follows:

(1) Increase the vane cut-back at the high energy end (output end) to 65.6 mm.

(2) Remove the 5° ramp (taper) on the high energy end (output end).

A sketch of these changes can be seen in Fig.14.

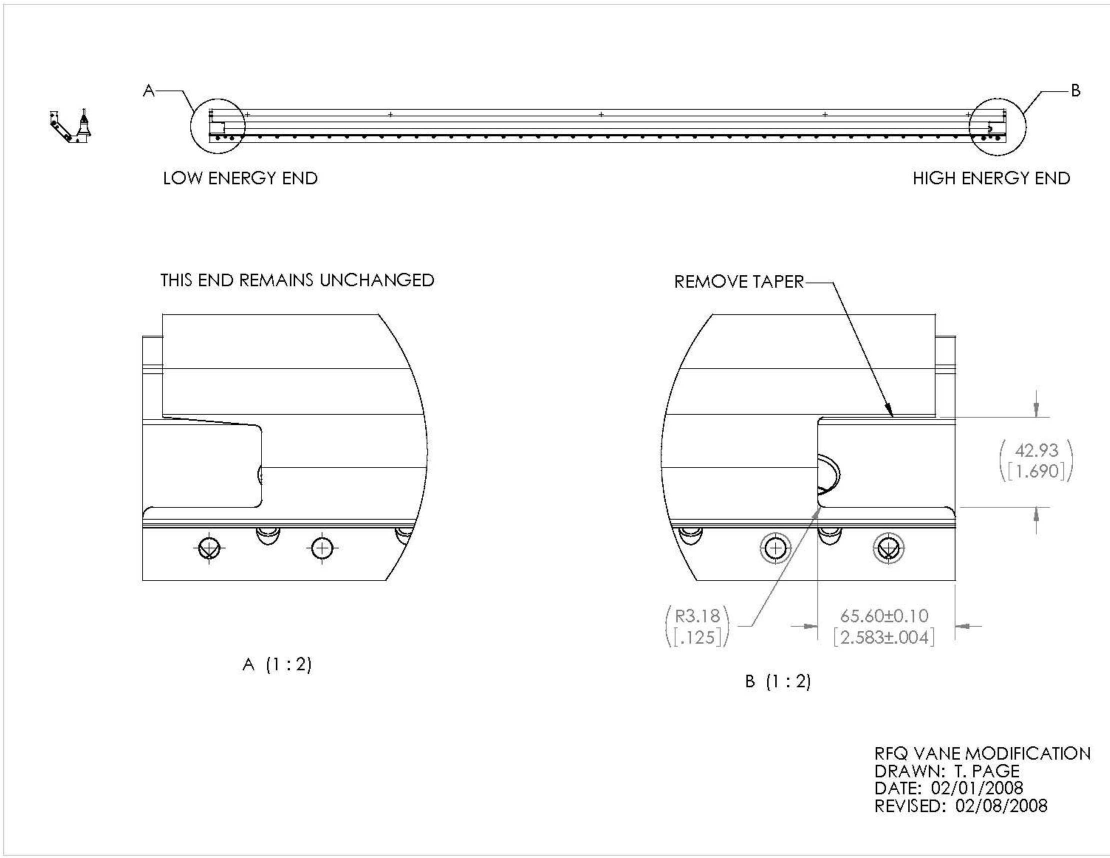

Fig.14. Sketch of proposed change to the high energy end of the RFQ vanes.

One possible issue was discovered when modifying the AccSys solid model of the RFQ vane. Making the cut-back deeper may cut into one of the vane mounting bolt holes. This may or may not be a problem depending on how accurate the model is compared to the real vane. Also, it appears that the cut-back only cuts into the pilot hole and will not affect the threaded portion of the hole. Again, this may or may not be a problem and is mentioned here as a precaution.

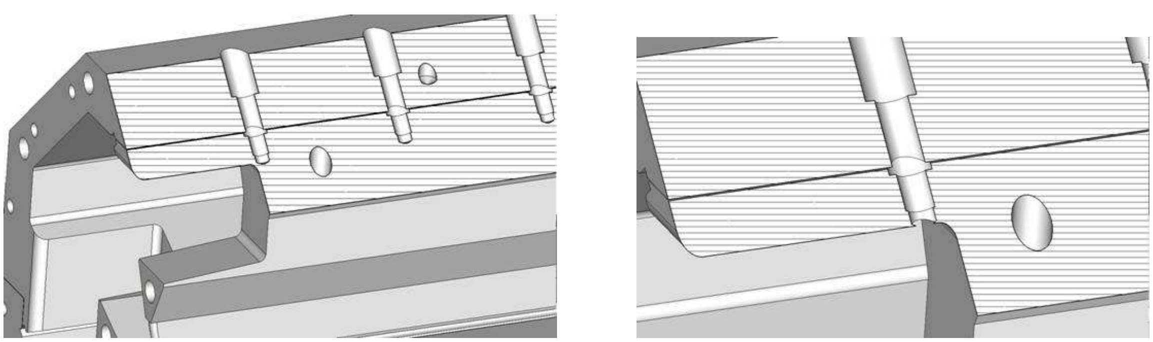

Fig.15. Cross-section through vane showing possible interference with bolt hole. (Left) Vane before machining. (Right) Vane after machining.